REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 15, 2004	3. REPORT TYPE AND DATES COVERED Final Tech 10/98 – 2/03

4. TITLE AND SUBTITLE

Space-Time Array Processing for Radar & Communications

5. FUNDING NUMBERS

Grant

ONR N0014-98-1-0892

6. AUTHOR(S)

Kevin Buckley, Richard Perry, and Joseph Teti

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Villanova University
Electrical and Computer Engineering
800 Lancaster Avenue
Villanova, PA 19085-1699

8. PERFORMING ORGANIZATION REPORT NUMBER

5-27626

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 North Quincy Street
Arlington, Va 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

a. DISTRIBUTION / AVAILABILITY STATEMENT

"Approved for Public Release; distribution is unlimited"

12. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We developed a new approach using EM derived algorithms for MLSE over channels having unknown FIR impulse coefficients with known statistics. The ML formulation for optimal sequence estimation over random channels is generally intractable to solve directly. However, the EM algorithm is a technique which can effectively be used to solve such intractable ML problems. Specifically, by using EM to marginalize over the channel coefficient distribution, optimal estimates of the transmitted sequence are derived which can achieve lower bit-error-rates than methods which jointly estimate both the transmitted sequence and the channel coefficients, and methods based on first optimally estimating the channel coefficients.

20041108 115

14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
none	none	unlimited	

Final Report
ONR Grant N00014-98-1-0892
Space-Time Array Processing for Radar and Communications

Executive Summary

In this report we overview the results for ONR Grant N00014-98-1-0892 entitled:

Space-Time Array Processing for Radar and Communications.

The grant supported research, as described below, conducted at Villanova University over a non-contiguous period of time from Oct. 1998 through Feb. 2003. In Year 1 of the Grant (10/98-9/99) was funded at $ 198,973.00. Year 2 of the Grant (10/99-9/00) was funded at $ 125,000.00. Year 3 of the Grant (10/00-9/01) was not funded by ONR. Year 4 of the Grant (10/01-9/02) was funded at $ 73,431.00, and a no cost extension was grated through 2/03.

The investigators for this research effort were Kevin Buckley (Professor), Richard Perry (Associate Professor), and Joseph Teti (Adjunct Professor) of the Electrical & Computer Engineering Department at Villanova University. Professors Buckley and Perry were involved throughout the grant period. Dr. Teti was fully involved the first year, involved at a reduced level the second. After the second year, funds were not available to support his activities.

The students who have been supported by this grant are: Anand Vaddiraju, Soujanya Yerra, Hai Chen, Jessica Bradley, John MacLachlan, Sangeetha Somayajula and Chunmei Wang. Mr. Vaddiraju and Miss Yerra graduated with MSEE degrees in September 1999. Miss Bradley graduated with a BSEE degree in May 1999. Mr. Chen graduated with a MSEE degree in Dec. 2000. Mr. MacLachlan graduated with a MSEE degree in Feb. 2001. Miss Somayajula graduated with a MSEE degree in July 2003. Miss Wang graduated with a MSEE degree in June 2004.

In this report we first review initial project objectives and tasks. These plans were based on the assumption that the originally granted funding level of $ 599,998.00 would be available over the originally proposed 3 year term of the grant. We then report, year by year, on results of the grant. Note that with the absence of funding in Year 3, research activity associated with this grant was reduced that year to the efforts of Professors Buckley and Perry. We were forced to prematurely terminate the planed research in the area of STAP, and to postpone any further significant investigation into multitarget tracking. With the additional funds provided for Year 4, two new MSEE students, Miss Wang. At that time we decided to focus on those proposed topics that we could contribute to most effectively with new research students over a one year period.

Since in Year 3 our efforts were limited to the presentation of some of our previous results, we do not report on Year 3 activities further below.

Project Objectives

As originally proposed, this research project was to consist of a two part investigation into signal processing for radar surveillance and digital communications.

Part I, entitled *Space-Time Adaptive Processing (STAP) Concepts for Circularly Symmetric Arrays (CSA's) for Airborne Surveillance Radar*, was concerned with the development of signal processing algorithms for next-generation airborne surveillance radars. It was an investigation into: space-time adaptive preprocessor design for radar array outputs; subsequent signal, interference and noise modeling; and post STAP detection and parameter estimation. This proposed research was focused on next-generation radar arrays, for which CSA's will replace existing rotating linear arrays.

The signal processing tasks that comprised the proposed effort for CSA based Airborne Surveillance Radar are summarized below:

- **Task 1:** Develop circularly symmetric array (CSA) architecture derived space-time adaptive processing (STAP) to formulate optimized two dimensional Doppler-azimuth spectra as a function of range cell.

- **Task 2:** Statistically characterize and model noise, clutter, interference and target signals to facilitate STAP algorithm development and performance evaluation.

- **Task 3:** Formulate post STAP target detection and parameter estimation techniques.

Part II, entitled *Algorithms for Distributed/Robust Detection, Parameter Estimation and Tracking*, addressed the development of optimum signal processing algorithms which effectively distribute computational load between distributed subsystems, where data originates, and a central fusion center. In addition to consideration of distributed processing, robustness to observation uncertainty, which is inevitable in any distributed sensing system was investigated. The primary focus of Part II was on distributed/robust signal processing for surveillance radars. A secondary investigation into robust multiuser digital communications took advantage of similarities between it and distributed/robust surveillance. Part II was a synergistic investigation where methods from digital communications were adapted and extended for distributed/robust radar surveillance, and the resulting algorithms were then being tailored for robust multiuser digital communications.

The signal processing tasks that comprised this effort for development of algorithms for robust/distributed detection, parameter estimation and tracking are summarized below.

- **Task 4:** Develop computationally efficient, distributed processing algorithms, based on the Expectation-Maximization (EM) approach to maximum likelihood and Bayesian estimation, for optimum and adaptive parameter estimation and tracking for radar and for sequence estimation in digital communications applications.

- **Task 5:** Develop computationally efficient, distributed processing algorithms for multitarget tracking and multiuser digital communication applications, based on generalized Viterbi algorithms.

- **Task 6:** Incorporate subspace and Bayesian modeling of observation uncertainty into the formulation of detection, parameter estimation and tracking problems discussed above, and thus into the EM and Viterbi algorithm based solutions resulting from Tasks 4 and 5.

Year 1 Results

Following are three sections overviewing the results from Year 1 of this research investigation. The three sections are:

1. Multitarget Tracking, which addresses Tasks 5 and 6 of the Project Objectives.

2. Robust Digital Communications, which addresses Tasks 4 and 6 of the Project Objectives.

3. Circular STAP Processing, which addresses Tasks 1 and 2 of the Project Objectives.

References in this section correspond to the **Project Bibliography** list at the end of this report which identifies documents written for this investigation.

Multitarget Tracking

In multitarget tracking, we started with time evolving sets of noisy measurements of detected targets and false alarms, and we associate the detections over time to form multiple target tracks. We then considered one class of track estimators, termed *Multiple Hypothesis Trackers (MHT's)* where measurement-to-track assignments are accomplished by considering all hypothesized track sets through the measurements. For MAP costs we computed Kalman filter generated innovations and *a priori* track set probabilities. Through the use of a *Maximum A Posterior (MAP)* criterion, we accounted for missed detections and false alarms.

The principal disadvantage of MHT is that the number of hypothesized track sets to be evaluated increases exponentially with time. Numerous approaches to hypothesis *pruning* and *merging* have been developed to reduce the computational burden of MHT and Bayesian trackers. (See [9,14] for discussions of existing pruning and merging methods.)

In Year 1 of this investigation, we developed a new MHT hypothesis pruning/merging algorithm based on a generalized Viterbi algorithm. For estimating K tracks, a trellis diagram of the measurements was first used to depict all track set hypotheses as trellis paths. Costs were computed using Kalman filters and *a priori* track set probabilities. Because the hypothesis costs do not satisfy the Markov condition required for Viterbi algorithm pruning optimality, a new K-track, list-Viterbi algorithm was employed to effectively prune the number of evaluated hypotheses to a manageable level. Further hypothesis reduction was implemented through merging and trellis truncation. The resulting *Viterbi MHT algorithm* is sequential. It is very flexible in that it can handle missed detections, false alarms and number-of-track estimation. It provides an ordered list of best track sets, which may have very similar costs but represent very dissimilar trajectories. This can be useful in subsequent data fusion. Compared to MHT algorithms that prune candidate track sets using teh standard Viterbi algorithm or "gating volumes", the new Viterbi MHT algorithm is less prone to loosing tracks.

In [15] we presented a preliminary version of the K-track, list-Viterbi algorithm which was derived from a maximum likelihood formulation. In [14] we extended this preliminary work, employing a MAP cost function and proposing an algorithm for joint estimation of the number of tracks, K, and the tracks themselves. In [9] we developed the new Viterbi MHT algorithm which, compared to previous versions, employs track merging to reduce computation and/or improve performance.

Robust Digital Communications

In Year 1 of this investigation, we addressed the problem of estimation of a sequence of digital communication symbols transmitted over an InterSymbol Interference (ISI) channel. We were concerned with solving the Maximum Likelihood Sequence Estimation (MLSE) problem in a manner which is robust to the knowledge of the channel coefficients. We treated the channel coefficients as unknown, but we assumed knowledge of their joint distribution, and we then marginalized over these coefficients.

For a known FIR channel, it is well known that Viterbi algorithm solves the MLSE problem. Although the computationally efficiency of this algorithm has lead to its broad use, the Viterbi algorithm requires knowledge of the channel (e.g. its impulse response). We derived new MLSE algorithms both for time-invariant channels and channels which vary significantly over a short block of symbols. We focused on blind methods (which do not employ training data).

An overview of methods which have been proposed previously for the unknown channel MLSE problem appears in [13]. These methods have been based on joint sequence/channel estimation (effective methods do not exist for channels which vary over a small block of data), channel estimation (which does not primarily address sequence estimation) followed by MLSE, or direct sequence estimation (which we pursue).

The Expectation Maximization (EM) method is an approach to development of iterative ML and Maximum a Posterior (MAP) estimation algorithms. For digital communications, this approach has been applied to the channel estimation problem. It has also been employed for MLSE with unknown nuisance channel, interference or receiver parameters. However, either simple prior distributions on the nuisance parameters were assumed in order to develop algorithms, or a high SNR approximation was derived.

We developed a new approach using EM derived algorithms for MLSE over channels having unknown FIR impulse coefficients with known statistics. The ML formulation for optimal sequence estimation over random channels is generally intractable to solve directly. However, the EM algorithm is a technique which can effectively be used to solve such intractable ML problems. Specifically, by using EM to marginalize over the channel coefficient distribution, optimal estimates of the transmitted sequence are derived which can achieve lower bit-error-rates than methods which jointly estimate both the transmitted sequence and the channel coefficients, and methods based on first optimally estimating the channel coefficients.

We derived EM algorithms for a variety of non-time-varying and fast time-varying channel models. In [13] we will present several robust MLSE algorithms for unknown non-time-varying channels. In [8] we proposed to do the same for fast time-varying channels. In [13] we present a detailed development for both non-time-varying and time-varying cases.

4

Circular STAP Processing

The first year's research activity on this topic focused primarily on Task 1, with some activity on Task 2 beginning during the last two months of the year. Progress had been made on Circular Symmetric Array (CSA) architecture derived space-time adaptive processing (STAP) with the development of full dimension performance modeling using ideal (known) space-time correlation matrices for signal, noise, clutter and jamming. The eigenstructure of the space-time correlation matrices was considered to evaluate the rank characteristics of the environment for a variety of "look" directions with respect to the platform velocity vector. Strategies for reducing the dimension of the problem also received attention.

Implementation and quantification of the sample support performance implications of using sampled space-time correlation matrices was considered. Classical treatment of this area bases sample support requirements on the assumptions of statistically homogeneity for the noise, interference and clutter correlation matrices. While this assumption is certainly reasonable for noise, it is often not the case for interference, and seldom the case for clutter. In addition, clutter statistics are often best described with mixture probability density functions, the parameterization of which is coupled to sensor resolution and space-time sampling characteristics. Research to assess the sample support requirements for more realistic environments of this type was conducted to support the formulation of reduced dimension STAP implementations.

Year 2 Results

Following are four sections overviewing the results of Year 2 of this research investigation. The four sections are:

1. Multitarget Tracking, which addresses Tasks 5 and 6 of the Project Objectives.

2. Robust Digital Communications, which addresses Tasks 4 and 6 of the Project Objectives.

3. Robust Source Localization, which does not directly address any of the Project Tasks in the Project Objectives, but which is an extension of results from Tasks 3 through 6, and is of interest to ONR.

4. Circular STAP Processing, which addresses Tasks 1 and 2 of the Project Objectives.

References in this section correspond to the **Project Bibliography** list at the end of this Report. lists documents written for this investigation.

Multitarget Tracking

In the Year 1 Report, we described a new approach we have developed for multitarget tracking. The resulting algorithm, which is of the Multiple Hypothesis Tracker (MHT) type and based on a Maximum A Posterior (MAP) optimization cost, incorporates a new hypothesis pruning/merging strategy. This new approach is termed the *Viterbi MHT algorithm*. As noted in the Year 1 Report, this approach was presented in [14,15].

In Year 2 extended the original Viterbi MHT algorithm along two lines. First, we implemented merging. Second, we incorporated time varying number-of-track estimation. These two extensions have been presented in, respectively, [9] and [10]. In Year [2], continuing this effort, we compared th *Viterbi MHT algorithm* with established target tracking algorithms, including: probabilistic data association filtering (PDAF) which was arguably the current standard; and probabilistic MHT (PMHT) which is an expectation-maximization (EM) approach. Compared to these alternatives, the *Viterbi MHT algorithm* performed favorably.

Also in Year 2, we developed a new, computationally efficient Linear Assignment Programming (LAP) algorithm. This computational algorithm, as an extension of the Karp algorithm (Karp, Networks, 1980), was novel in that it accounts for missed target detections (as well as for false alarms which the Karp algorithm can handle). With this development complete, we then turned our attention to incorporating our new LAP computational algorithm into an "N-best" multiple target tracking algorithm which was similar to that proposed by Danchick & Newman (IEEE Trans. on AES, Apr. 1993) which is based on the Karp computational algorithm. We also looked at incorporating this new LAP computational algorithm into the Viterbi MHT algorithm.

Also in Year 2, we developed an expectation-maximization (EM) algorithm for multitarget measurement-to-data association estimation. In this algorithm, as an extension to multiple targets of a Viterbi Data Association (VDA) algorithm proposed by Pulford and Logothetis (Proc. Conf. on Decision & Control, 1997) for single target tracking, multiple tracks are handled in the estimation (E) step of the EM iteration by using the K-track Viterbi computational algorithm we had already developed for the Viterbi MHT multitarget tracking algorithm. This new EM multitarget tracking algorithm is different from the Probabilistic MHT (PMHT) algorithm recently proposed by Streit and Luginbuhl (Proc. Conf. on Sig. & Data Proc. of Small Targets, 1994) in which EM is used to estimate the track states of multiple targets. This new algorithm is a logical extension of methods we were investigating at that time.

Robust Digital Communications

In the Year 1 Report, we motivated and described a new approach to robust digital communication, whereby prior distributions on nuisance channel parameters are used to marginalize over the unknown channel parameters so as to solve the maximum likelihood (ML) or maximum a posterior (MAP) sequence estimation problem. That new approach was based on the expectation-maximization (EM) algorithmic approach. As noted in the Year 1 Report, we first presented this work in [13]. Subsequently, we presented extension of this original work in [7,8].

In Year 2 we extended this approach so as to incorporate further knowledge of the channel coefficients in the form of linear constraints. We presented this in [12]. We have continued to investigate time-varying channels, focusing on fast-fading Raleigh channels which result from moving transmitters in multipath propagation environments. Results of this effort were presented in [8].

From a computational viewpoint, the EM algorithmic approach represents an attractive alternative to direct solutions to ML or MAP estimation problems. However, for discrete parameter estimation (e.g. sequence estimation for digital communications) we and other researchers had noticed that initialization of the EM algorithm is critically important to assure convergence to a good solution. Because of this, we began considering computationally efficient direct solutions to ML and MAP sequence estimation problems for unknown, fast time-varying channels. In Year 2 we developed new algorithms for this, in some cases based on optimum Viterbi algorithm searches and in some cases based on a suboptimal but effective Generalized Viterbi Algorithm (GVA) approach to Per Survival Processing (PSP). We reported on this in [7]. Contrary to claims in the literature, we proved that EM algorithms for sequence estimation are not guaranteed to converge to a local minimum of the ML or MAP negative log likelihood function. This is an important result because, although it does not discount the utility of EM based sequence estimators, it clarifies the issue of EM algorithm convergence for this application, and points to the need for careful consideration of EM algorithm initialization for discrete parameter estimation. In [1] we presented this non-convergence proof and contrast performance of our EM and our GVA PSP based sequence estimators.

Robust Source Localization

As a byproduct of our investigation into EM algorithms for multiple target tracking and digital communication sequence estimation, we developed a new approach to optimum source location parameter estimation. This approach is based on marginalizing over the source signal amplitudes given prior information of their distributions in the form of both joint probability density functions and linear constraints. Previously, it had been shown by Radich and Buckley (Signal Processing Letters, Oct. 1997) (and by others) that, for certain noninformative prior distributions, marginalizing over nuisance signal amplitudes can result in measurable location parameter estimator performance improvement. The challenge has been to develop an algorithmic approach applicable to any prior distribution on the signal amplitudes. In [11], we described an EM algorithmic approach that meets this challenge.

STAP Processing

During Year 2 we investigated hot and cold terrain scatter clutter models, with the particular emphasis on deriving more accurate models and on clutter rank issues for both linear and circular configured arrays. We considered both asymptotic characteristics and finite sample effects. Complementing this, we developed Monte Carlo simulations to evaluate STAP filter performance (e.g. output SNIR). Based on this study, we began to investigate the performance of several CFAR post-STAP detectors in complex, realistic hot and cold clutter, jammer and noise situations. In [18] a report was presented on a study we conducted on the performance of the Generalized Likelihood Ratio Test (GLRT), the Adaptive Matched Filter (AMF) and the Adaptive Cosine Estimator (ACE) detectors in heterogeneous clutter environments with steering vector mismatch.

Year 4 Results

In Year 4 we focused our limited resources and temporal horizon on Tasks 4 and 5 of the proposed plan. Specifically, we continued our investigation into computationally efficient time-evolving, discrete hypothesis testing algorithms. We concentrated on the further development of generalized Viterbi algorithms for unknown time varying intersymbol interference digital communications channel environments, and extended our results to high performance iterative algorithms and to space time processing applications.

Beginning with generalized Viterbi algorithms we had developed previously in this investigation (for multitarget tracking and digital communications over unknown, time varying intersymbol interference channels), we developed a soft Viterbi algorithm and a forward/backward symbol-by-symbol MAP algorithm which can be used to generate soft decision statistics that can be used in Turbo and other high performance iterative equalization/decoding schemes. The novelty of this work, which we reported on in [2], is that it effectively extended iterative decoding schemes to the realm of unknown fast time varying ISI channels.

We also extended our work on efficient demodulation algorithms for unknown, time-varying ISI channels to the decoding of Space-Time Block Codes (STBCs). At the time, STBC decoding algorithms were being developed for fading channels; but not if they were unknown, fast time-varying and with intersymbol interference. We developed a generalized Viterbi based per-survivor processing algorithm for this problem. We also developed a Turbo decoding algorithm for this challenging application. These results we reported, respectively, in [3] and [2].

Project Bibliography

1. Hai Chen, Richard Perry and Kevin Buckley, "On MLSE algorithms for unknown fast time varying channels," *IEEE Transactions on Communications*, Vol. 51, No. 5, May, 2003.

2. Sangeetha Somayajula, Kevin Buckley and Richard Perry, "Soft output decoding algorithm for space-time block codes over unknown time varying channels with intersymbol interference", *Proc. 37-th Asilomar Conference on Signals, Systems and Computers, Asilomar CA,* Oct. 2003.

3. Chunmei Wang, Kevin Buckley & Richard Perry, "Space-time block coding over unknown frequency and time selective channels", *CISS - 37-th Annual Conference on Information Sciences and Systems,* Mar. 2003.

4. Diane Pytel, Kevin Buckley and Richard Perry, "Multi-user maximum likelihood based sequence estimation for unknown, frequency selective, fast time varying channels", *Proc. 35-rd Asilomar Conference on Signals, Systems and Computers, Asilomar CA,* Oct. 2001.

5. Hai Chen, Richard Perry & Kevin Buckley, "MAP sequence estimation for fading ISI channels", *CISS - 35-th Annual Conference on Information Sciences and Systems,* Mar. 2001.

6. Hai Chen, Richard Perry and Kevin Buckley, "Direct and EM-based MAP sequence estimation with unknown time-varying channels", *ICASSP-2001,* April 2001.

7. Hai Chen, Kevin Buckley and Richard Perry, "Time-recursive maximum likelihood based sequence estimation for unknown ISI channels", *Proc. 34-rd Asilomar Conference on Signals, Systems and Computers, Asilomar CA,* Oct. 2000.

8. Richard Perry, W. Andrew Berger and Kevin Buckley, "EM algorithm for sequence estimation over Gauss-Markov ISI channels", *ICC-2000,* June 2000.

9. Kevin Buckley, Anand Vaddiraju, and Richard Perry, "A new pruning/merging algorithm for MHT multitarget tracking", *Radar-2000,* May 2000.

10. Jessica Bradley, Kevin Buckley and Richard Perry, "Time-Recursive number-of-tracks estimation for MHT", *SPIE-2000,* pp. 510-520, Apr. 2000.

11. Richard Perry and Kevin Buckley, "Maximum likelihood source localization using the EM algorithm to incorporate prior parameter distributions," *1st IEEE SAM Workshop,* pp. 12.6.1-5, Mar. 2000.

12. Kevin Buckley and Richard Perry, "Sequence estimation over linearly-constrained random channels", *CISS - 34-th Annual Conference on Information Sciences and Systems,* pp. FA7.7-12, Mar. 2000.

13. Richard Perry, W. Andrew Berger and Kevin Buckley, "EM algorithm for sequence estimation over random ISI channels", *Proc. 33-rd Asilomar Conference on Signals, Systems and Computers, Asilomar CA,* pp. 295-299, Oct. 1999.

14. Richard Perry, Anand Vaddiraju and Kevin Buckley, "Trellis Structure Approach to Multitarget Tracking", Proc. ASAP Workshop, Lexington, MA, March 1999.

15. Richard Perry, Anand Vaddiraju and Kevin Buckley, "Multitarget List Viterbi Tracking Algorithm", *Proc. Asilomar Conference on Signals, Systems and Computers,* Asilomar CA, November 1998.

16. Chunmei Wang, *Space-Time Coding Over Unknown Frequency and Time Selective Fading Channels,* MSEE Thesis, Dept. of Electrical & Computer Engineering, Villanova University, June 2004.

17. Sangeetha Somayajula, *Iterative Decoding of Space-Time Block Codes Over Unknown Time-Varying Channels with Intersymbol Interference,* MSEE Thesis, Dept. of Electrical & Computer Engineering, Villanova University, July 2003.

18. John MacLachlan, *The Study of Space-Time Adaptive Processing and Radar Detection Algorithms Using Monte Carlo Simulations,* Independent Study, Dept. of Electrical & Computer Engineering, Villanova University, Feb. 2001.

19. Hai Chen, *Direct and EM-based MAP Sequence Estimation with Unknown Time-varying Channels,* MSEE Thesis, Dept. of Electrical & Computer Engineering, Villanova University, Dec. 2000.

20. A. Vaddiraju, *A New Multiple Mode Algorithm for Maneuvering Targets,* MSEE Thesis, Dept. of Electrical & Computer Engineering, Villanova University, Sept. 1999.

21. S. Yerra, *Maximum Likelihood Sequence Estimation for Gaussian Minimum Shift Keying over Unknow Multipath Channels,* MSEE Thesis, Dept. of Electrical & Computer Engineering, Villanova University, Sept. 1999.